Direct Photons at RHIC

Klaus Reygers
University of Heidelberg
for the PHENIX Collaboration

Why Direct Photons
in Nucleus-Nucleus Collisions (I) ?

Time ➡️
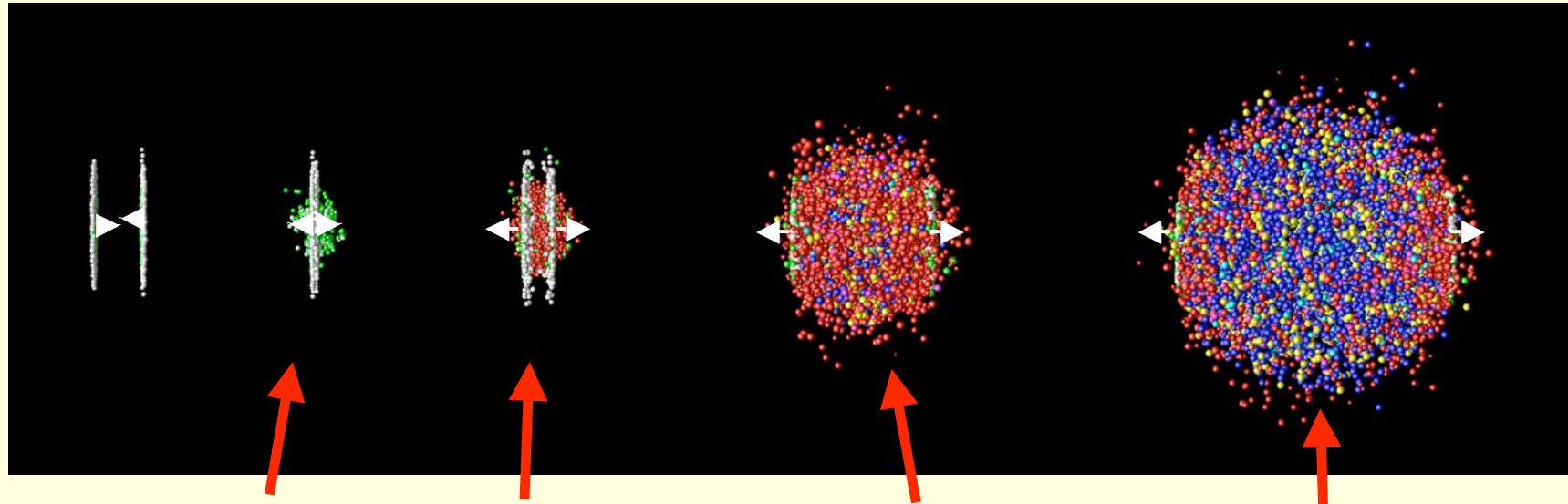
Initial hard parton-parton scatterings (→ hard γ)

Thermalized medium (QGP!?), $T_0 > T_c$, $T_c \approx 170 - 190$ MeV (→ thermal γ)

**Phase transition QGP → hadron gas**

Freeze-out

- **The hope is to create a thermalized medium that can (locally) be characterized by a temperature T.**

- **Once produced photons leave the fireball unscathed → experimental access to the temperature of the fireball**

Why Direct Photons in Nucleus-Nucleus Collisions (II) ?

- **Direct photon yields at low p_T (< 5 GeV/c)**

  - **Measure thermal photons $\rightarrow$ initial temperature of the fireball**

  - **Find further photon sources related to presence of the QGP (e.g. photons from jet-plasma interaction)**
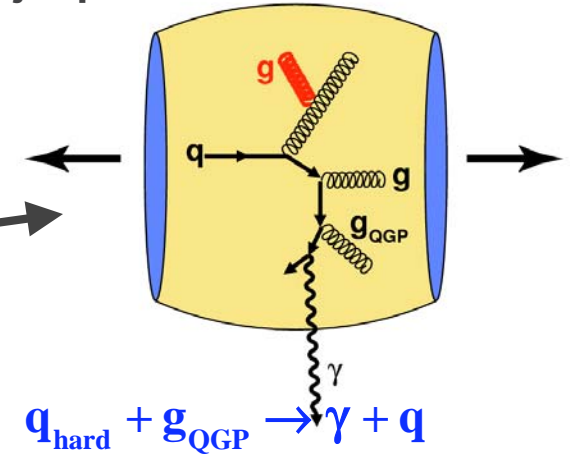
- **Direct photon yields at high p_T**

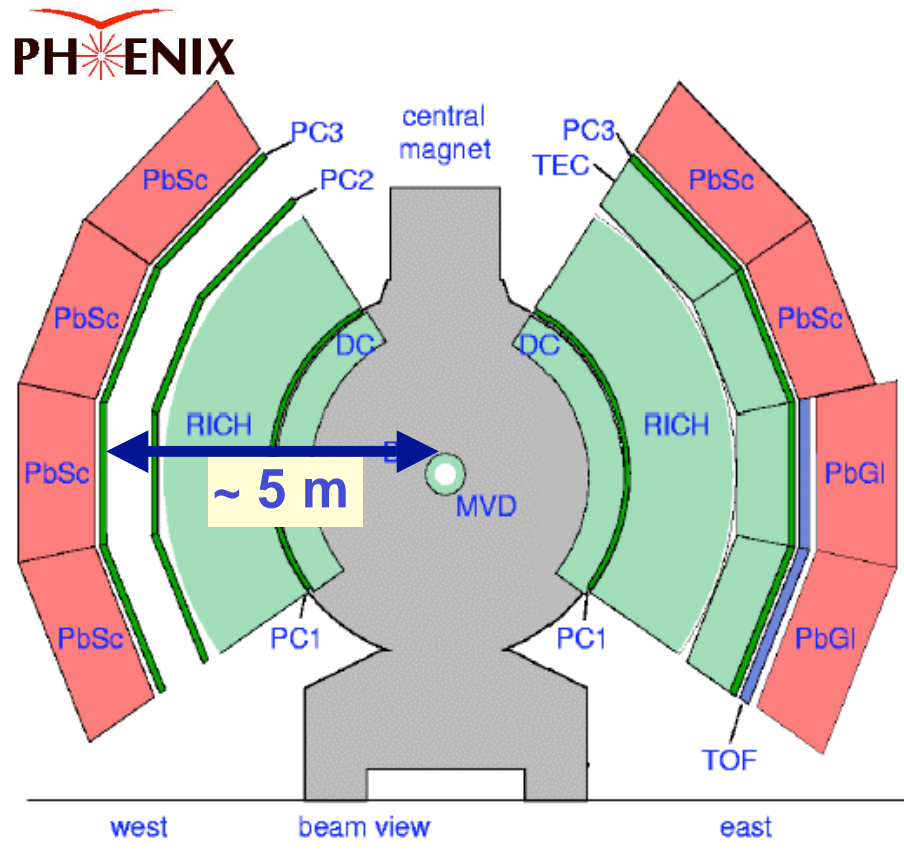 - **Confirm point-like scaling for hard processes**

- **Direct γ - hadron azimuthal correlations**

  - **p+p: measure fragmentation function**

  - **A+A: $E_\gamma = E_{jet} \rightarrow$ study parton energy loss for partons with known initial energy**

Photons from jet-plasma interaction:

$$q_{hard} + g_{QGP} \rightarrow \gamma + q$$

γ-h azimuthal correlations

transverse plane
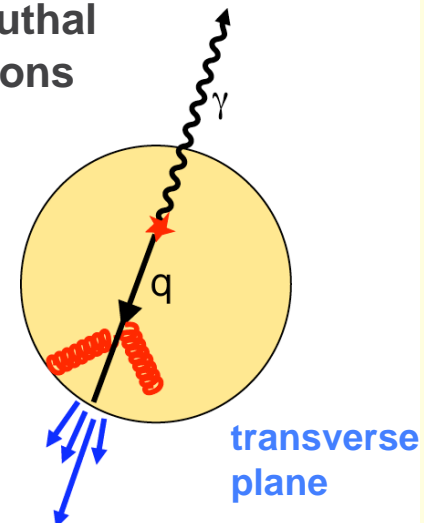
PHENIX: Photon and Electron Detectors

Pseudorapidity coverage : |η| < 0.35

- **EMCal:**
  PbSc (6 sectors) + PbGl (2 sectors)

- **PbSc :**
  - **Highly segmented lead scintillator sampling calorimeter**
  - **Module size: 5.5 cm x 5.5 cm x 37 cm**

- **PbGl:**
  - **Highly segmented lead glass Cherenkov calorimeter**
  - **Module size: 4.0 cm x 4.0 cm x 40 cm**

- **Ring Imaging Cherenkov Detector (RICH):**
  - **Electron identification (together with *E/p* matching in EMCal)**
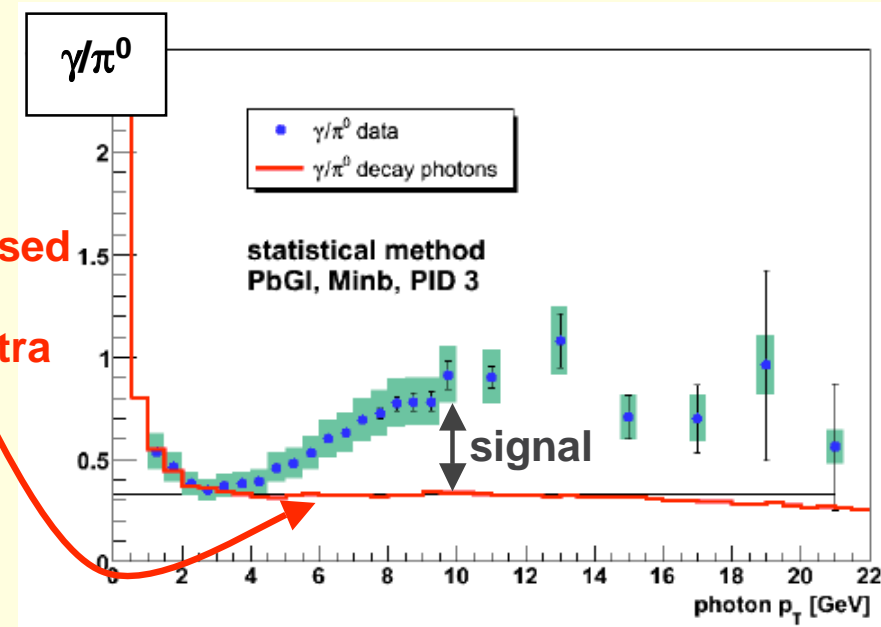 - **No signal for charged pions with *p* < 4.6 GeV/*c***

How Do We Measure Direct Photons in PHENIX?

- **Intermediate and high p_T:**
  Real photons with EMCal

  - ◆ **Statistical Subtraction
    (typically no isolation cut)**

$$\gamma_{\text{direct}} = \gamma_{\text{inclusive}} - \gamma_{\text{decay}}$$

$$= \left(1 - \frac{\gamma_{\text{decay}}/\pi^0}{\gamma_{\text{inclusive}}/\pi^0}\right) \cdot \gamma_{\text{inclusive}}$$

Calculated based on measured π^0 und η spectra

γ/π^0

- γ/π^0 data
- γ/π^0 decay photons

statistical method
PbGl, Minb, PID 3
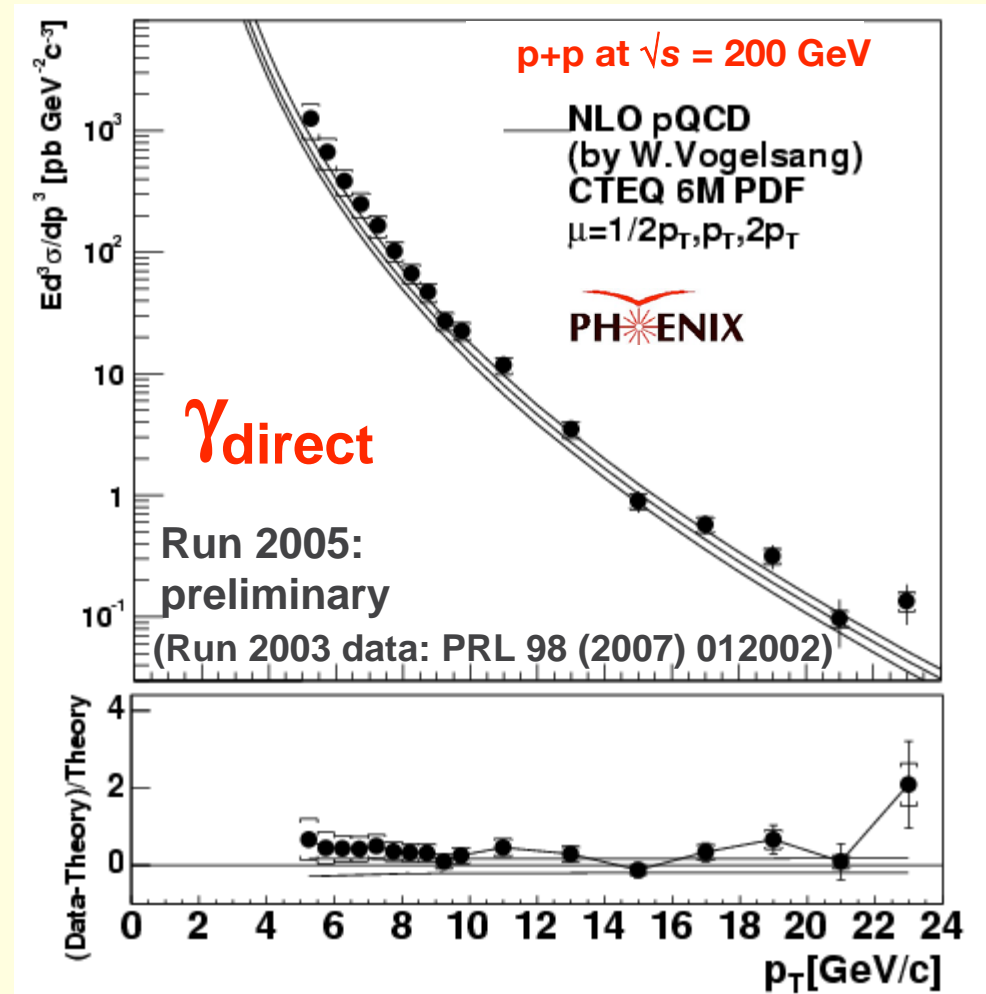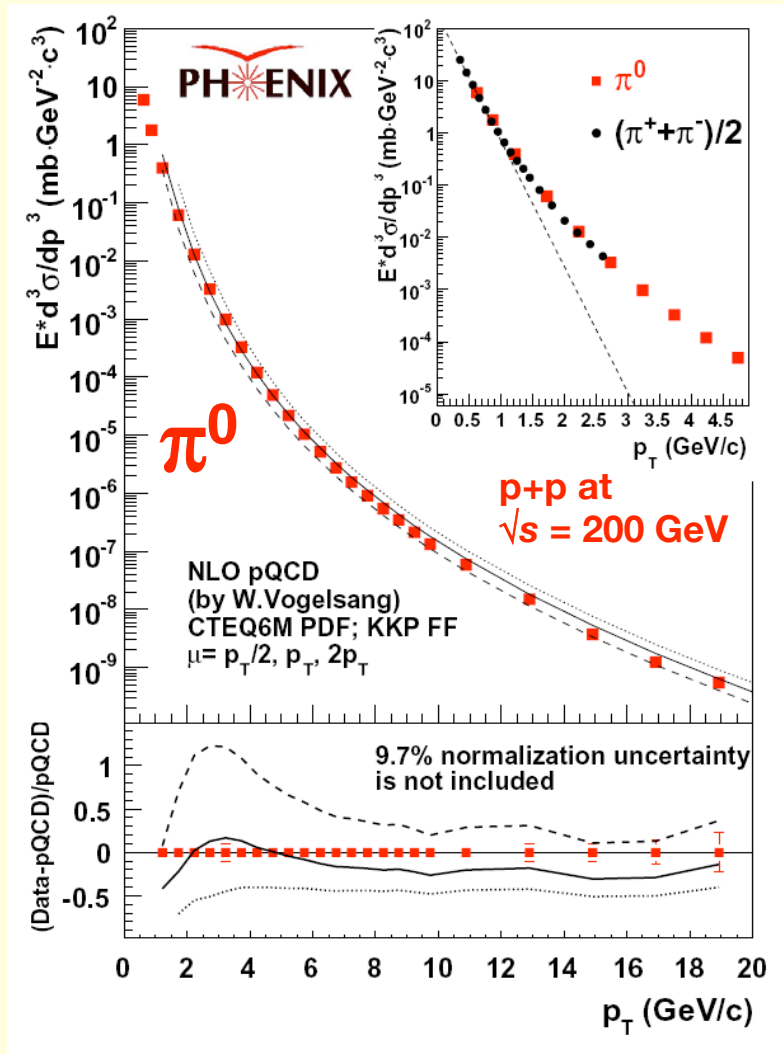
signal

photon p_T [GeV]

- **Low p_T:**
  Virtual photons ($\gamma^* \rightarrow e^+e^-$) with RICH (internal conversion)
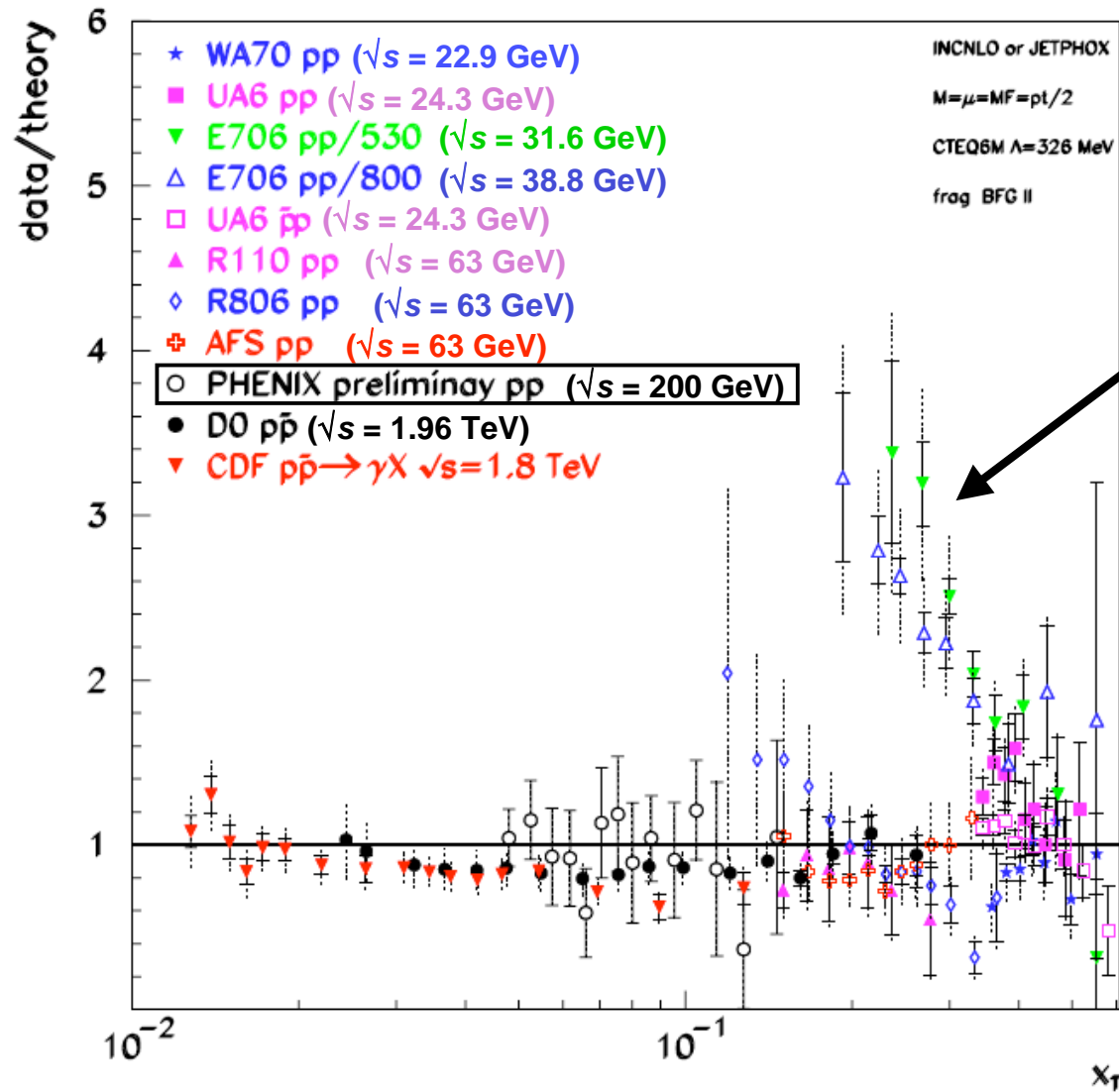
  - ◆ **Assumption:**
    $$\frac{\gamma_{\text{direct}}}{\gamma_{\text{inclusive}}} = \left.\frac{\gamma^*_{\text{direct}}}{\gamma^*_{\text{inclusive}}}\right|_{m_{ee} < 30\,\text{MeV}}$$

γ_{direct} and π^0 Spectra in p+p at $\sqrt{s}$ = 200 GeV: Agreement with NLO perturbative QCD

Agreement with pQCD: Prerequisite for jet quenching calculations in A+A
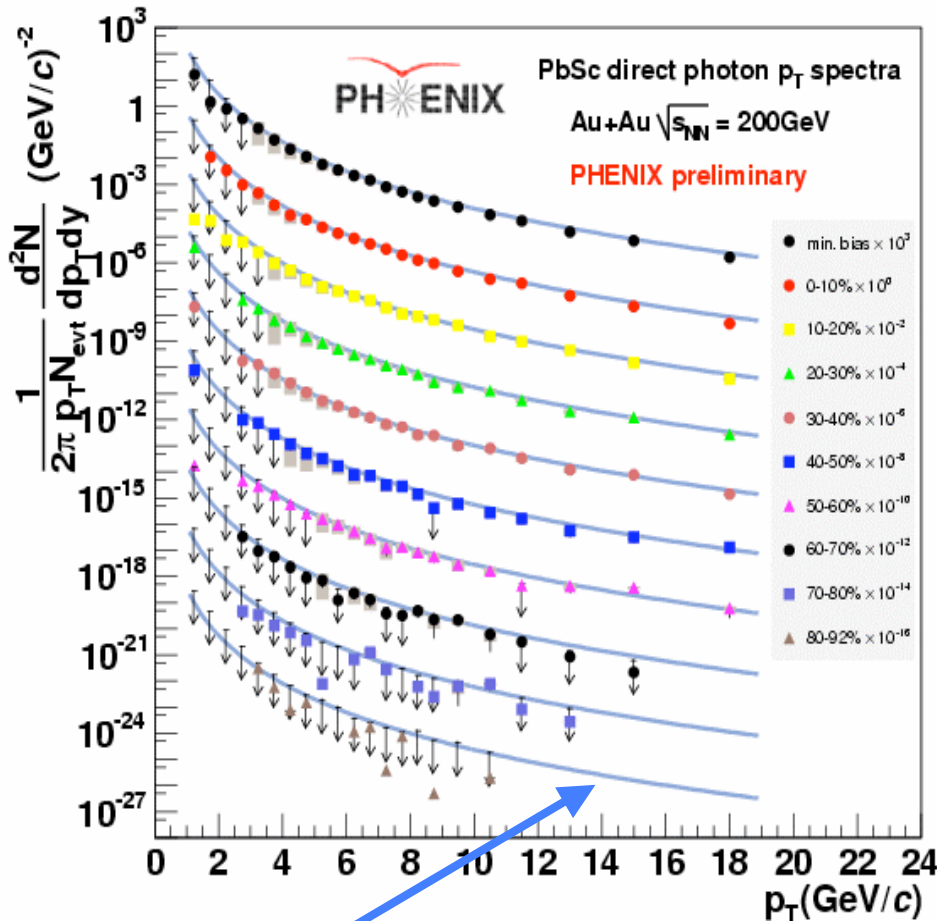
Direct Photon Production in p+p: Data/Theory for various $\sqrt{s}$

WA70 pp ($\sqrt{s}$ = 22.9 GeV)
UA6 pp ($\sqrt{s}$ = 24.3 GeV)
E706 pp/530 ($\sqrt{s}$ = 31.6 GeV)
E706 pp/800 ($\sqrt{s}$ = 38.8 GeV)
UA6 p̄p ($\sqrt{s}$ = 24.3 GeV)
R110 pp ($\sqrt{s}$ = 63 GeV)
R806 pp ($\sqrt{s}$ = 63 GeV)
AFS pp ($\sqrt{s}$ = 63 GeV)
PHENIX preliminay pp ($\sqrt{s}$ = 200 GeV)
D0 p̄p ($\sqrt{s}$ = 1.96 TeV)
CDF p̄p→γX $\sqrt{s}$=1.8 TeV

INCNLO or JETPHOX
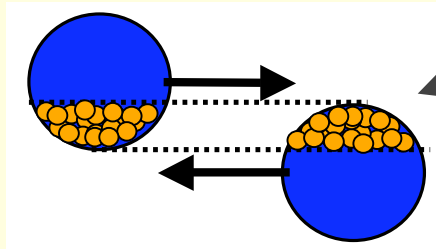M=μ=MF=pt/2
CTEQ6M Λ=326 MeV
frag BFG II

- **NLO pQCD describes direct photon data from $\sqrt{s}$ = 20 – 2000 GeV**

- **Only exception: Data from E706**

Aurenche et al., Phys. Rev. D 73 (2006), 094007

# Direct Photon Yields in Au+Au: (Approximate) N_{coll} Scaling

PbSc direct photon p_T spectra

PHENIX

Au+Au $\sqrt{s_{NN}}$ = 200GeV

PHENIX preliminary

- min. bias × 10^3
- 0-10% × 10^0
- 10-20% × 10^{-2}
- 20-30% × 10^{-4}
- 30-40% × 10^{-6}
- 40-50% × 10^{-8}
- 50-60% × 10^{-10}
- 60-70% × 10^{-12}
- 70-80% × 10^{-14}
- 80-92% × 10^{-16}

Blue lines: N_{coll} scaled pQCD p+p cross-section

N_{coll} = number of inelastic nucleon-nucleon collisions

Factorization:

parton distribution

parton distribution
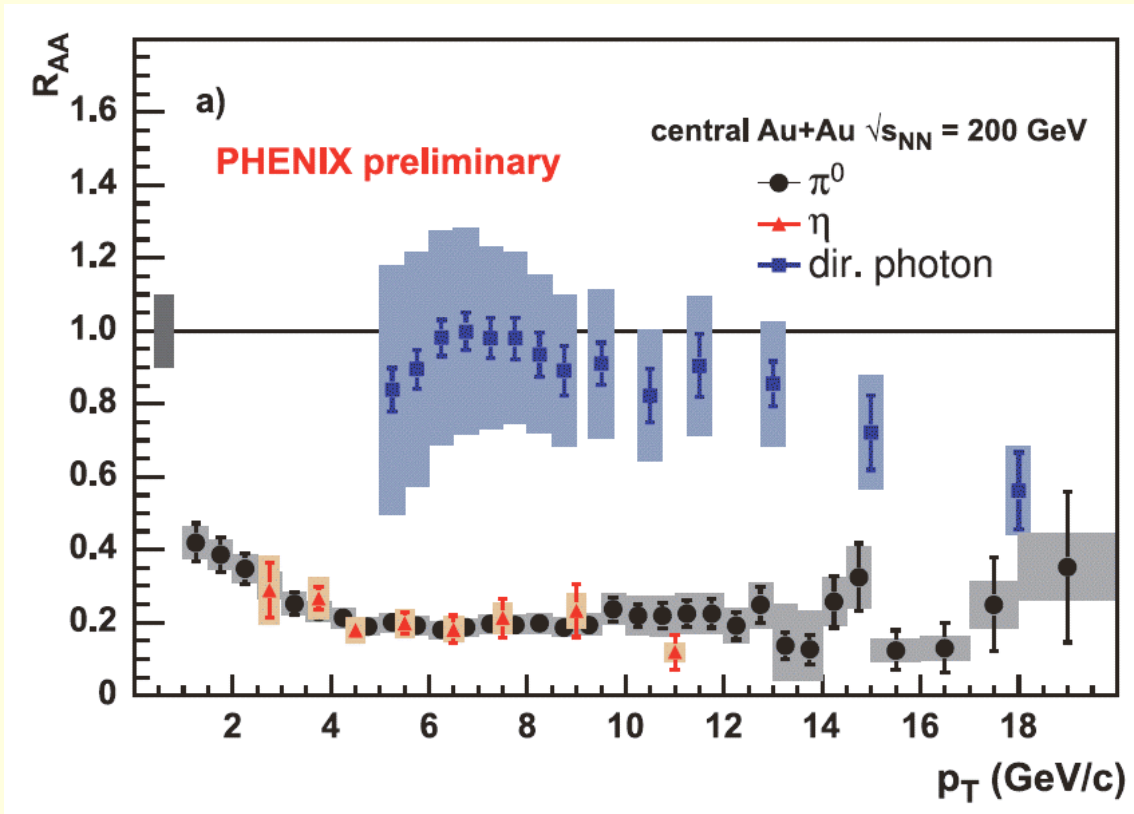
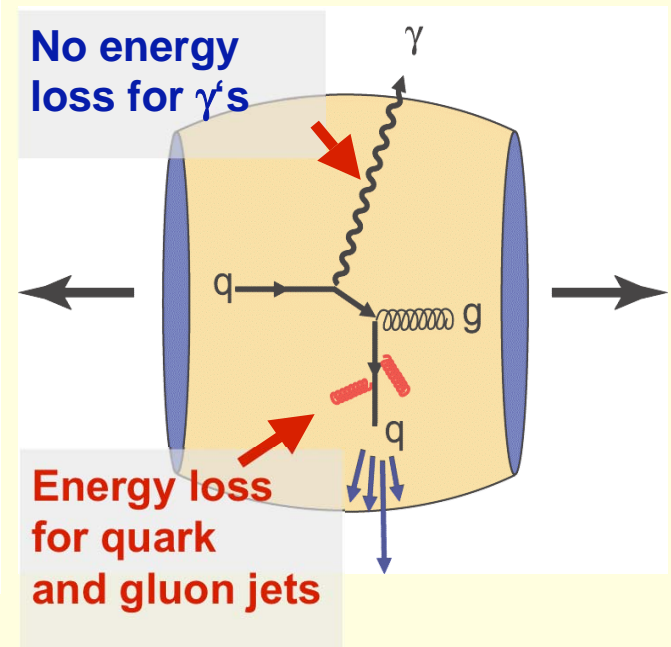hard scattering

γ_{direct}

frag-mentation

Jet
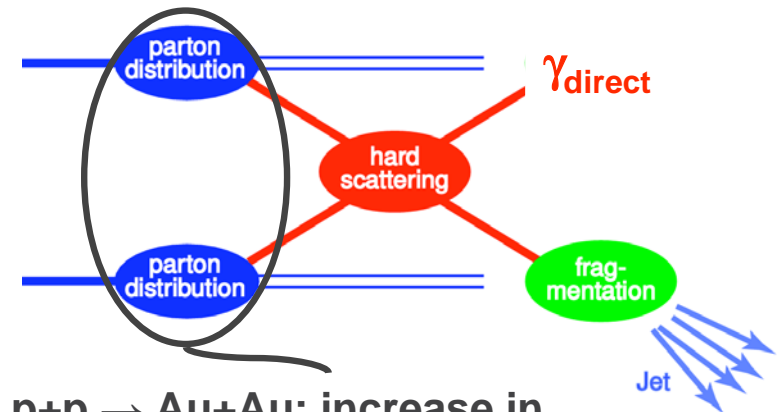
p+p → Au+Au: increase in parton-luminosity per collision

- **QCD factorization implies N_{coll} scaling of hard scattering yields**
- **Indeed observed for direct γ**

γ_{direct} and π^0's in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV: Evidence for Parton Energy Loss

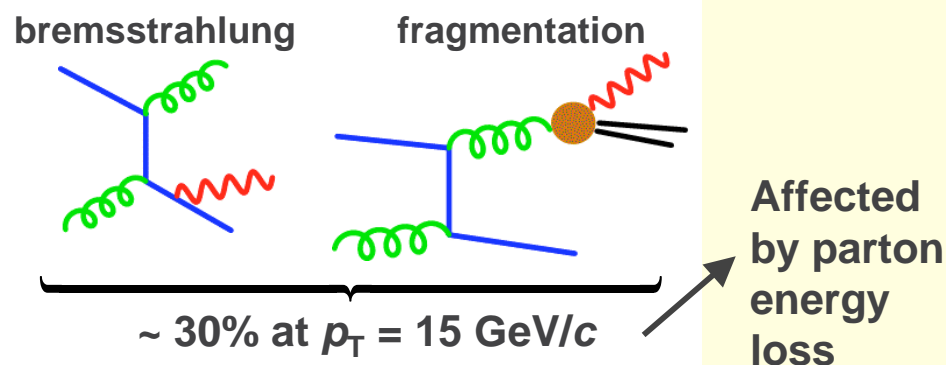$$R_{AA} = \frac{dN/dp_T\big|_{A+A}}{\langle N_{\text{coll}} \rangle \times dN/dp_T\big|_{p+p}}$$

No energy loss for γ's

Energy loss for quark and gluon jets

π^0's and η's are suppressed, direct photons are not: Evidence for parton energy loss (jet quenching)

Direct γ $R_{AA} < 1$ for $p_T > 14$ GeV/c ?

Direct Photon Au+Au $\sqrt{s_{NN}} = 200$ GeV, 0-10%

PHENIX preliminary

Isospin effect
+ anti-shadowing
+ parton *E* loss

— Arleo
--- Arleo EKS
— Arleo EKS $20 < \omega_c < 25$ GeV

PH✳ENIX

bremsstrahlung   fragmentation

~ 30% at $p_T = 15$ GeV/c
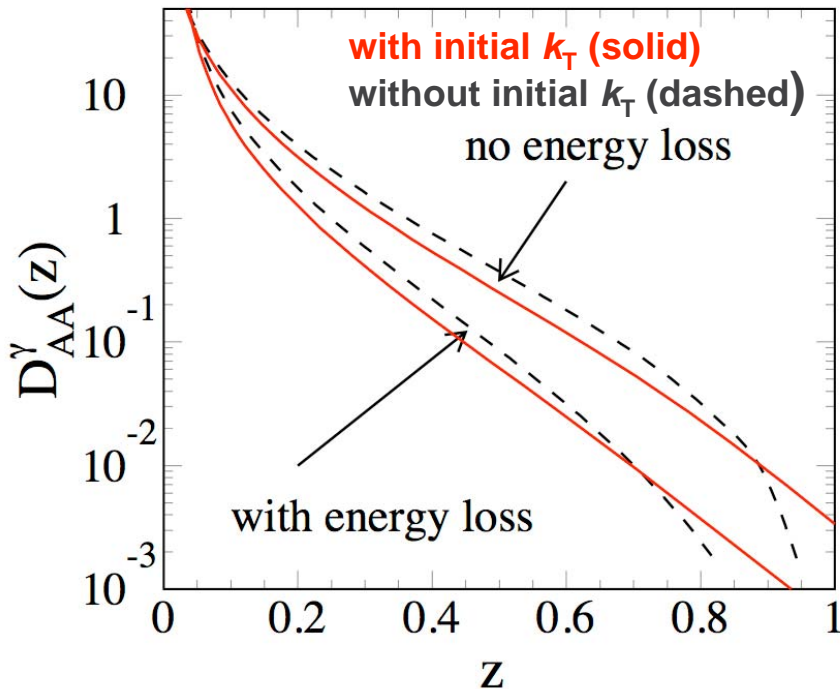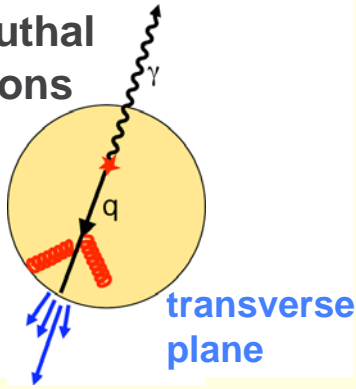
Affected by parton energy loss
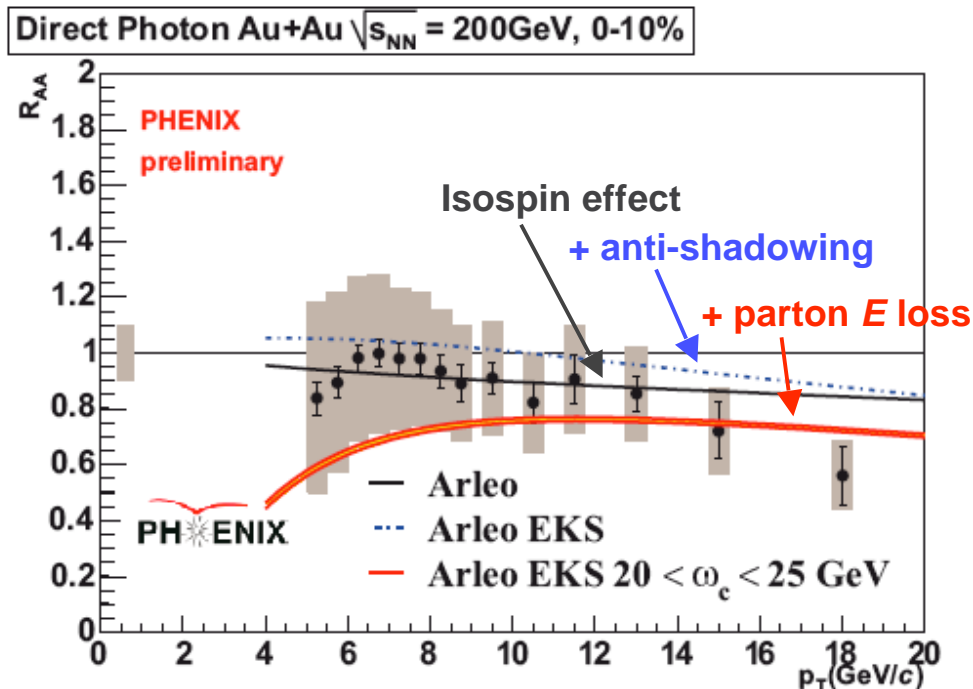
- *$R_{AA} < 1$ expected due to isospin effect (difference between p+p, p+n, n+n)*

- **Further contribution: Suppression of bremsstrahlung and fragmentation photons due to parton energy loss**

- **Experimental issue: Correction for the merging of the two showers from π^0 decay photons needs to be double-checked ($\rightarrow$ wait for final data)**

γ-Triggered Away-Side Correlations: Basic Idea

γ-h azimuthal correlations

γ

q

transverse plane

with initial k_T (solid)
without initial k_T (dashed)
no energy loss

with energy loss

$D^\gamma_{AA}(z)$

z

- **p+p:**
  (Effective) jet fragmentation functions can be extracted from γ-hadron azimuthal correlations (modulo initial k_T effect)

- **A+A:**
  Modification of fragmentation function provides information on parton energy loss

- **Variables:**

$$z_T = \frac{p_T^h}{p_T^\gamma}$$

$$D(z_T) = \frac{1}{N_{\text{trig}}} \frac{dN(z_T)}{dz_T}$$

Wang, Huang, Phys.Rev.C55:3047-3061,1997

γ-Triggered Away-side Correlations: Jet Fragmentation Function in p+p and Au+Au
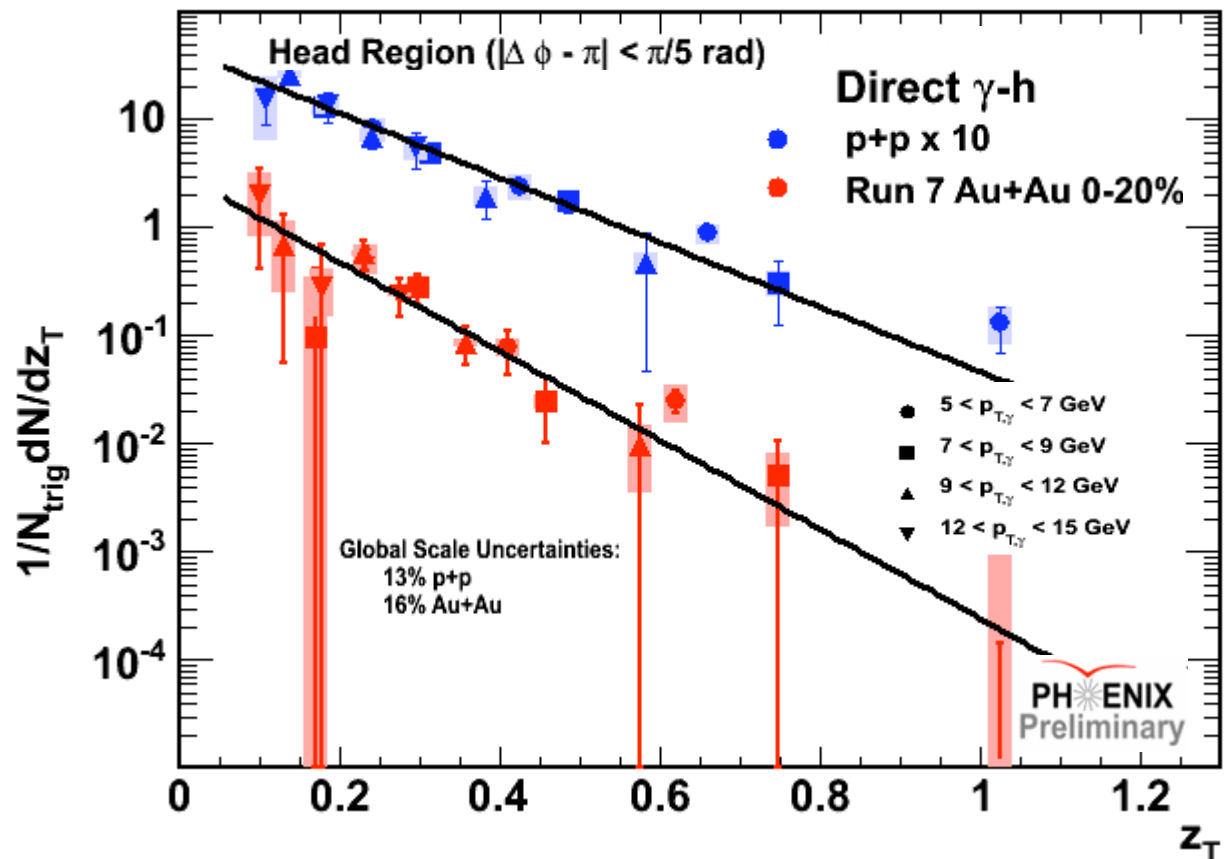
- **Fit effective FF's with**

$$\frac{\mathbf{d}N}{\mathbf{d}z_T} = Ne^{-bz_T}$$

- **p+p:** $b = 6.89 \pm 0.64$
- **Au+Au:** $b = 9.49 \pm 1.37$
- **Difference reflects influence of the medium**
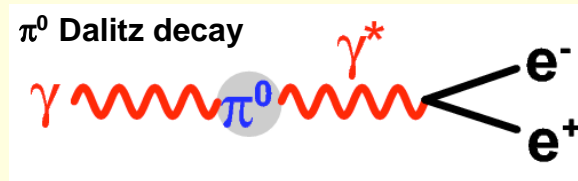
Direct Photons via Internal Conversion

- **Motivation:**
  Measure where thermal photons are expected and calorimetric measurements are difficult

- **Internal conversion**

  - **Any source of real photons also emits virtual photons**
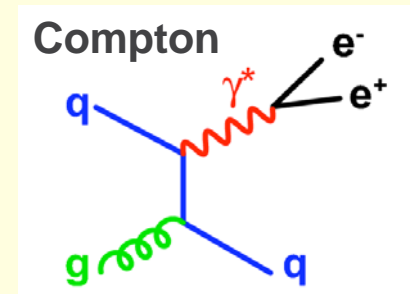
  - **Well known example:** π^0 **Dalitz decay**

  - **Rate and m_{ee} distribution calculable in QED (Kroll-Wada formula)**

- **Hadron decays: $m_{ee} < M_{hadron}$**

- **Essentially not such limit for point-like processes**

Compton

Improve signal-to-background ratio by measuring e⁺e⁻ pairs with $m_{ee} > \sim M_{pion}$

Kroll-Wada Formula

Number of virtual photons per real photon (in a given $\Delta\eta \; \Delta\phi \; \Delta p_T$ interval):

$$\frac{1}{N_\gamma}\frac{\mathrm{d}N_{ee}}{\mathrm{d}m_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1 - \frac{4m_e^2}{m_{ee}^2}}\left(1 + \frac{2m_e^2}{m_{ee}^2}\right)S$$
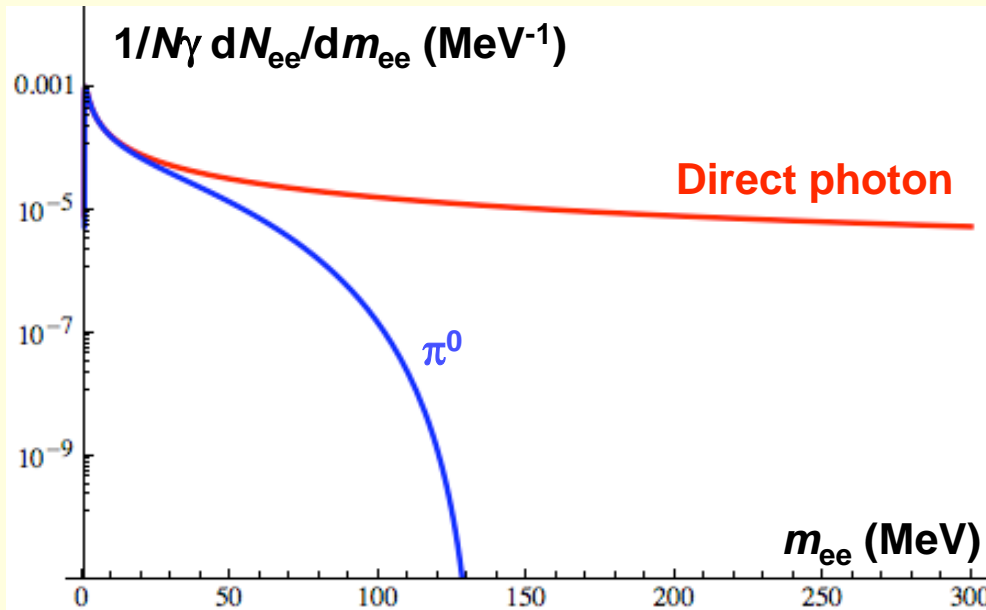
Hadron decay:

$$S = |F(m_{ee}^2)|^2\left(1 - \frac{m_{ee}^2}{M_h^2}\right)^3$$

form factor

Point-like process:

$$S \approx 1$$
$$(\text{for } p_T^{ee} \gg m_{ee})$$

$1/N\gamma \; \mathrm{d}N_{ee}/\mathrm{d}m_{ee} \; (\mathrm{MeV}^{-1})$
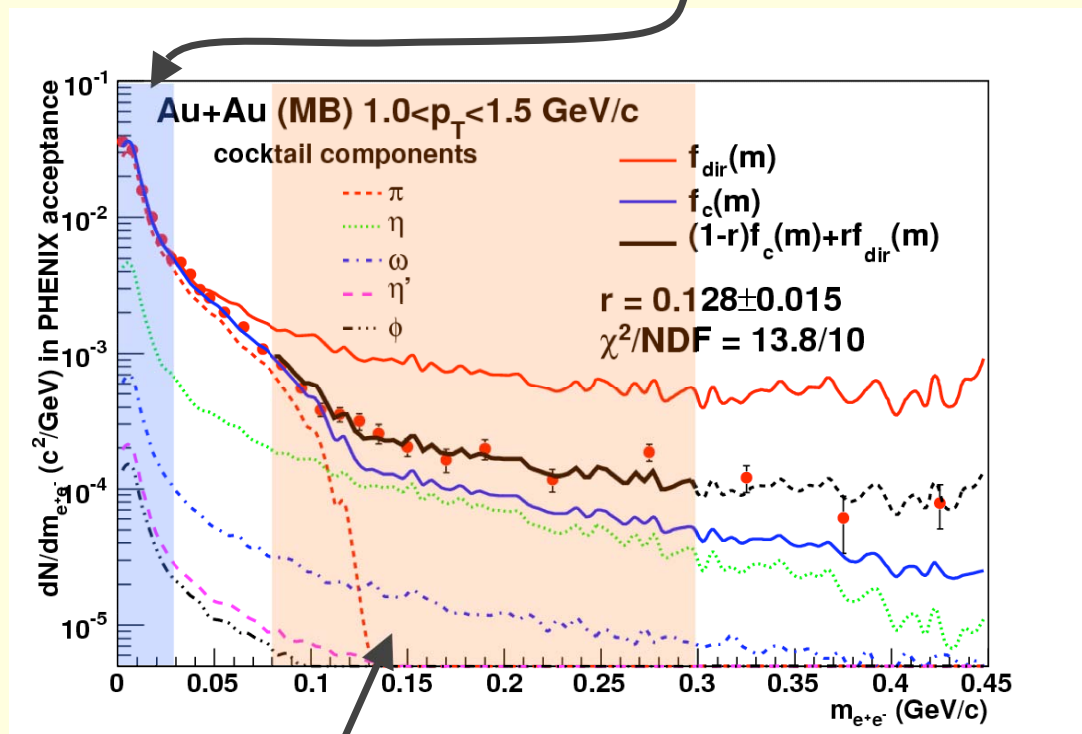
Direct photon

π^0

m_{ee} (MeV)

About 0.001 virtual photons with $m_{ee} > M_{\text{pion}}$ for every real photon

→ **Avoid the π^0 background at the expense of a factor 1000 in statistics**

Extraction of the Direct Photon Signal: Two-Component Fit

$$f(m_{ee}) = (1-r) \cdot f_{\text{cocktail}}(m_{ee}) + r \cdot f_{\text{direct}}(m_{ee})$$
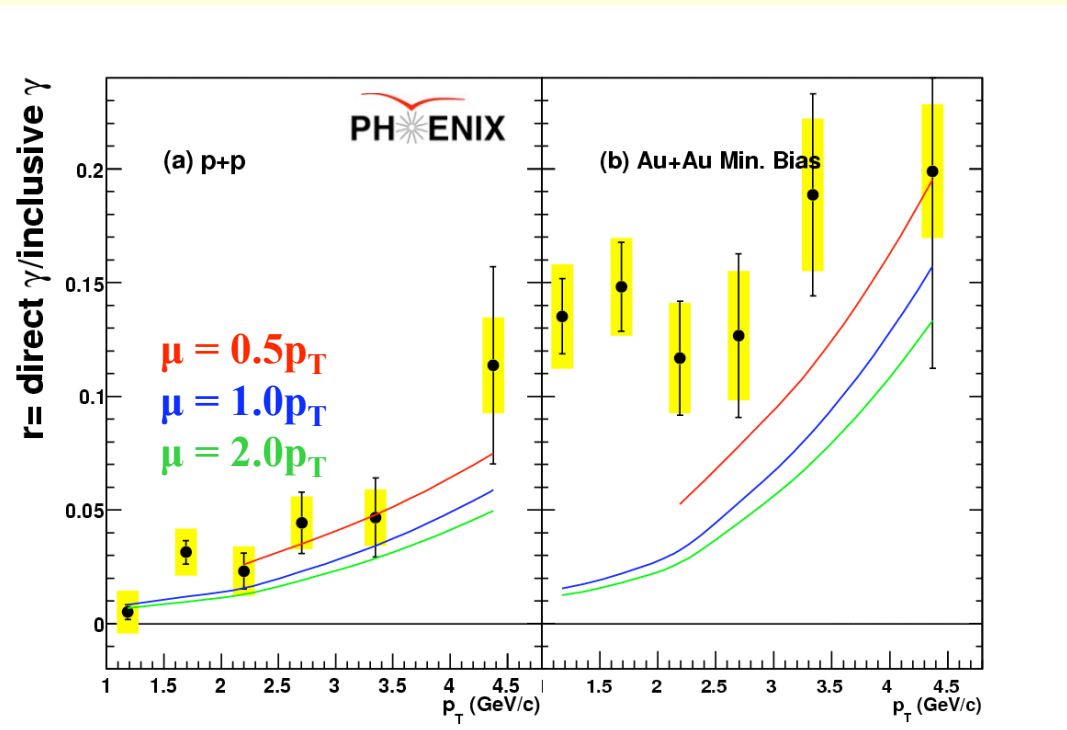
Separately normalized to data at $m_{ee} < 30$ MeV

- **Interpret deviation from hadronic cocktail (π, η, ω, η', ϕ) as signal from virtual direct photons**

- **Extract fraction r with two-component fit**

$$r = \left. \frac{\gamma^*_{\text{direct}}}{\gamma^*_{\text{inclusive}}} \right|_{m_{ee} < 30\,\text{MeV}}$$

- **Fit yields good χ^2/NDF (13.8 / 10)**

Au+Au (MB) $1.0 < p_T < 1.5$ GeV/c

cocktail components

- - - π
- - - η
- - - ω
- - - η'
- - - ϕ

— $f_{\text{dir}}(m)$
— $f_c(m)$
— $(1-r)f_c(m)+rf_{\text{dir}}(m)$

$r = 0.128 \pm 0.015$
χ^2/NDF = 13.8/10

dN/dm$_{e^+e^-}$ (c^2/GeV) in PHENIX acceptance

m$_{e^+e^-}$ (GeV/c)

Fit range: $80 < m_{ee} < 300$ MeV

Direct Photon Fraction in p+p and Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

(a) p+p

PHENIX

$\mu = 0.5 p_T$
$\mu = 1.0 p_T$
$\mu = 2.0 p_T$

(b) Au+Au Min. Bias

r= direct γ/inclusive γ

p_T (GeV/c)

PHENIX, arXiv:0804.4168v1 [nucl-ex]

- Lowest p_T ever measured in p+p

- Comparison to NLO pQCD (colored lines)

- p+p: Agreement

- Au+Au: Strong enhancement at low p_T

Low p_T Direct Photon Spectra in p+p and Au+Au at $\sqrt{s_{NN}}$ = 200 GeV
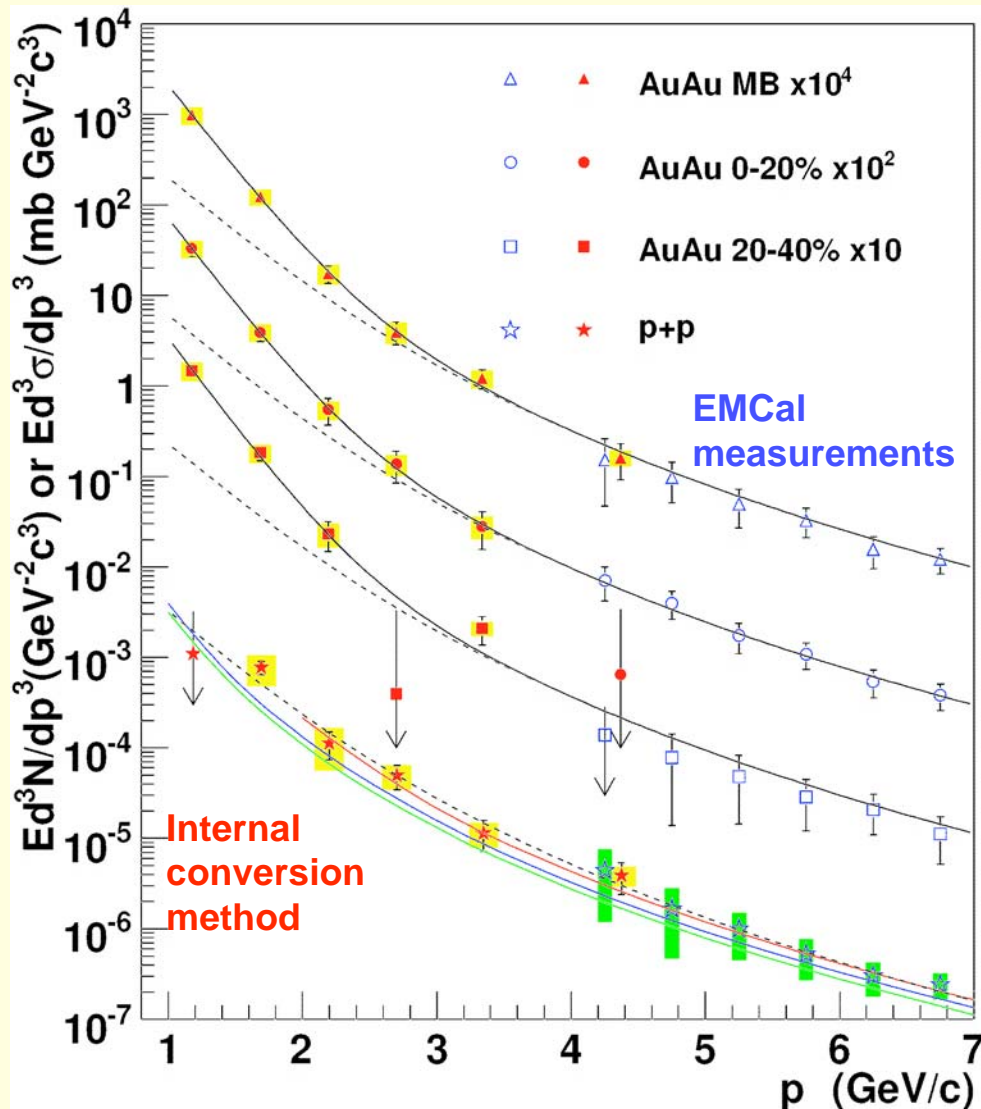
- **p+p: spectrum described with**
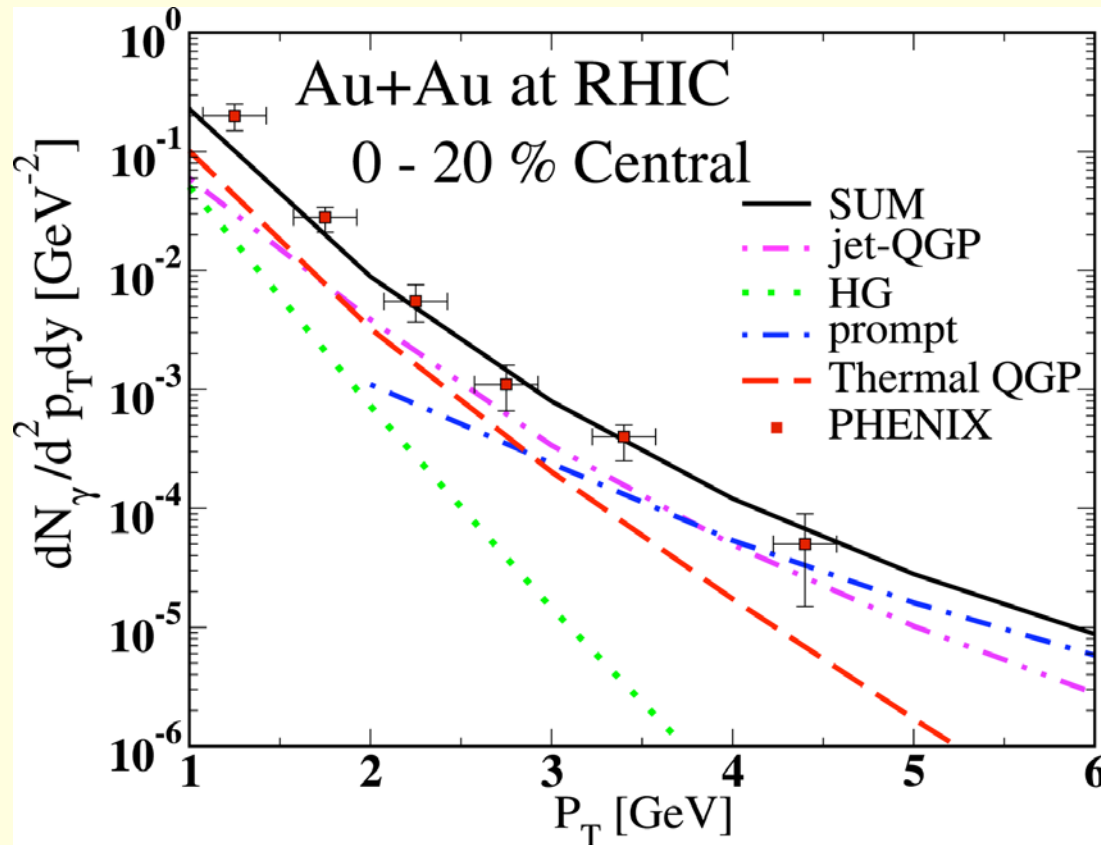
$$f_{p+p}(p_T) = A \cdot (1 + p_T^2 / b)^{-n}$$

- **Au+Au:**
Enhancement above p+p described by an exponential (as expected for a thermal source)

$$f_{Au+Au}(p_T) = \frac{N_{coll}}{\sigma_{NN}^{inel}} \times f_{p+p}(p_T) + B \times e^{-\frac{p_T}{T}}$$

- **Slope parameter (0-20%):**
T = (221 ± 23 ± 18) MeV

Expected to be a lower limit for the initial temperature!

PHENIX, arXiv:0804.4168v1 [nucl-ex]

Model Comparison

C. Gale, arXiv:0904.2184v1

Similar conclusions for essentially all hydro models on the market

- **Model space-time evolution with ideal hydro**

- **This calculation (arXiv:0904.2184v1)**

  - **Hydro starts early (τ_0 = 0.2 fm/*c*) to take pre-equilibrium photons into account**

  - **Thermal equilibrium expected at τ_0 = 0.6 fm/*c* ($T_{initial}$ = 340 MeV)**

  - **Photons from jet-plasma interaction needed**

- *$T_{initial} > T_c \approx$ 170 - 190 MeV $\rightarrow$ evidence for the formation of a quark-gluon plasma*

PHENIX Low p_T Direct Photon Data: Comparison with Different Hydro Models
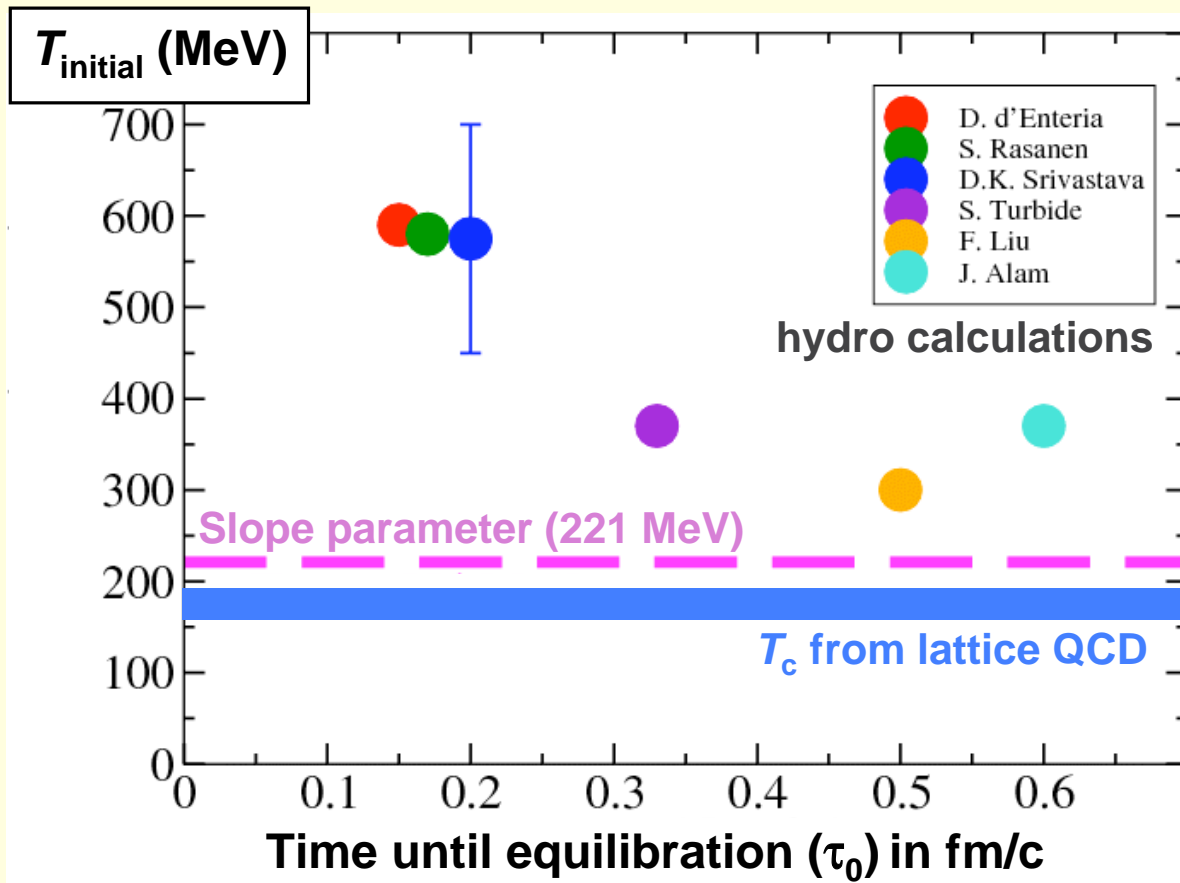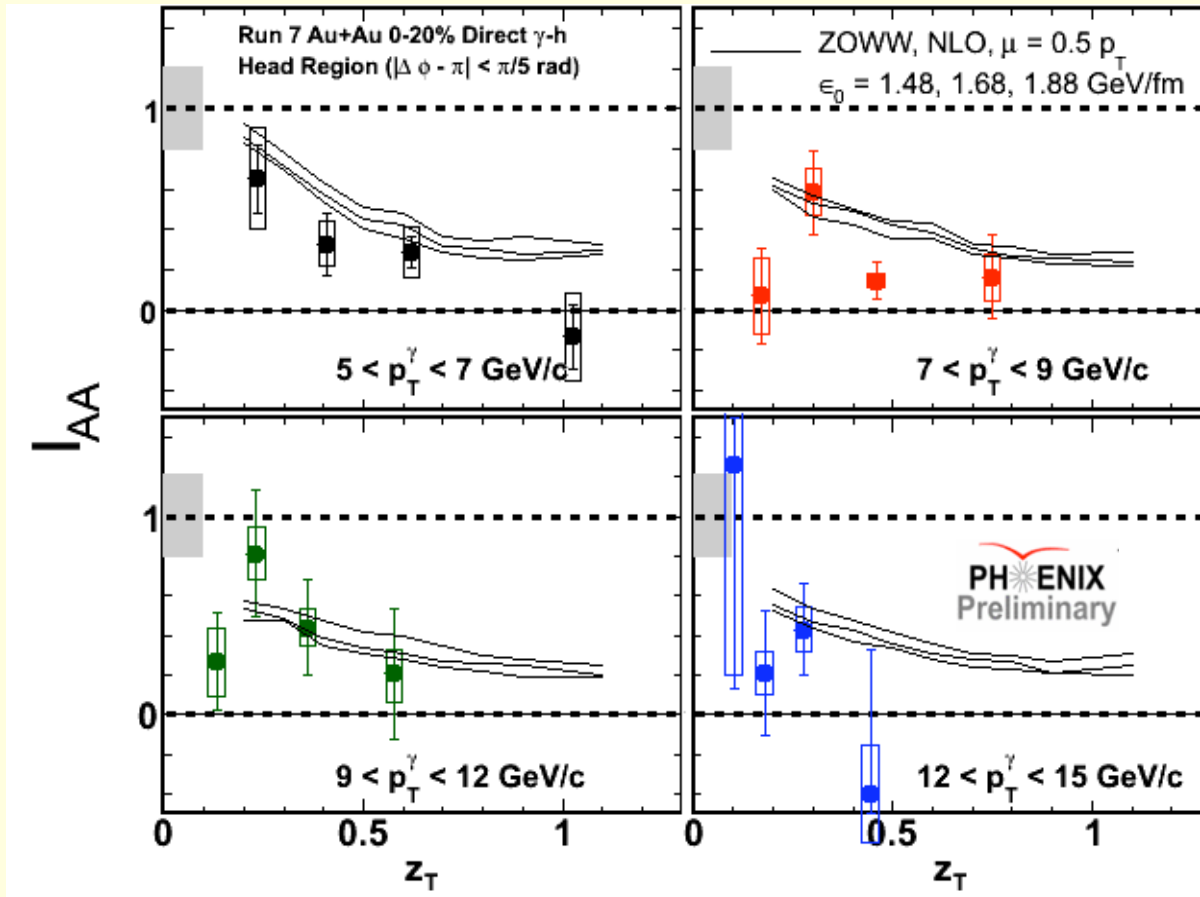

Initial temperature above T_c in all models

Conclusions

- **High p_T π^0's and direct photons:**
  π^0's are suppressed whereas direct photons follow scaling expected for hard processes:

  - π^0 suppression is a final state effect (most likely jet quenching)

- **γ-triggered away-side correlations:**
  Will allow to quantify parton energy loss via modified fragmentation functions

- **Low p_T direct photons:**
  Enhanced production of direct photons with $1 < p_T < 4$ GeV/c in Au+Au w.r.t. p+p provides evidence for thermal photons as expected from a quark-gluon plasma

# Extra Slides

γ-Triggered Away-side Correlations: Results

$$I_{AA} = D_{AA}(z_T) / D_{pp}(z_T)$$

Run 7 Au+Au 0-20% Direct γ-h
Head Region ($|\Delta\phi - \pi| < \pi/5$ rad)

ZOWW, NLO, $\mu = 0.5\ p_T$
$\epsilon_0 = 1.48,\ 1.68,\ 1.88$ GeV/fm

$5 < p_T^\gamma < 7$ GeV/c

$7 < p_T^\gamma < 9$ GeV/c

$9 < p_T^\gamma < 12$ GeV/c

$12 < p_T^\gamma < 15$ GeV/c

PH*ENIX Preliminary

I_{AA}, z_T

- **Different z_T regions probe different regions of the fireball (arXiv:0902.4000v1)**

- **Agreement with NLO pQCD + parton energy loss: Indication that energy loss in different regions of the fireball is understood**

NLO calculation:
Zhang et al. (ZOWW), arXiv:0902.4000v1

Direct Photon Spectra in p+p vs. NLO pQCD
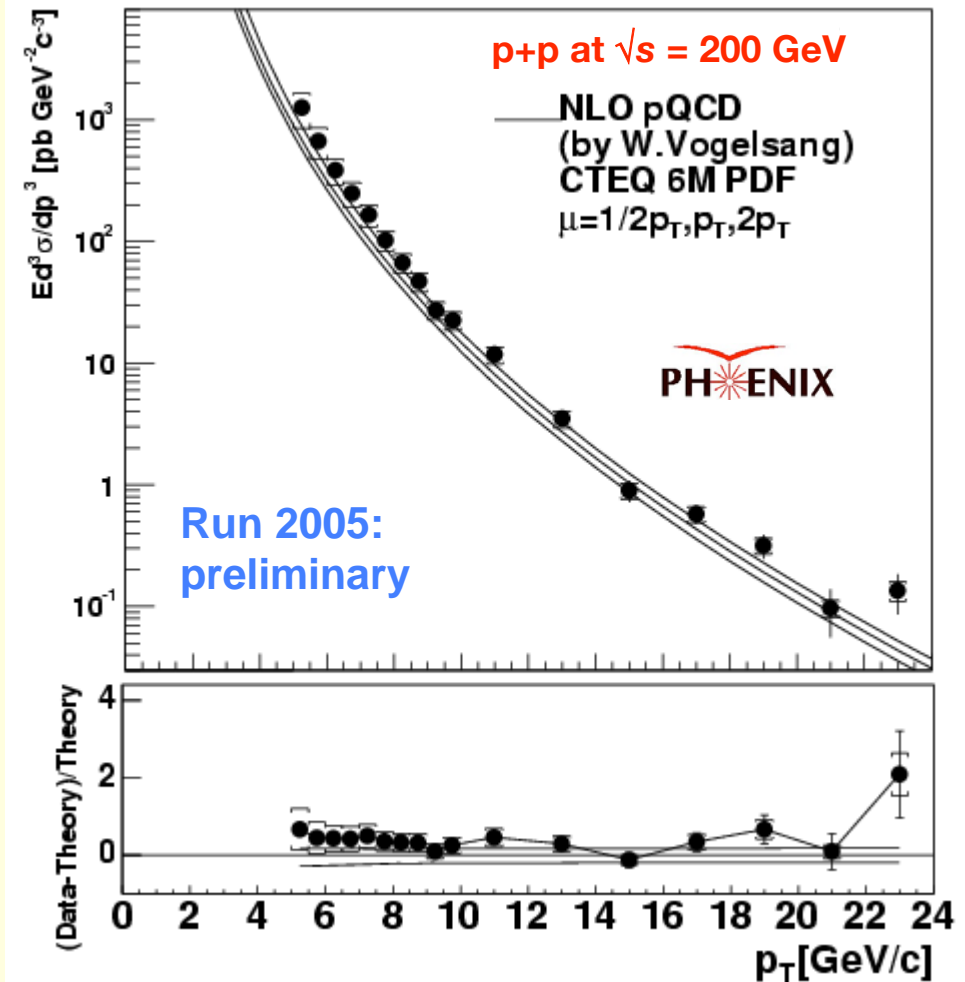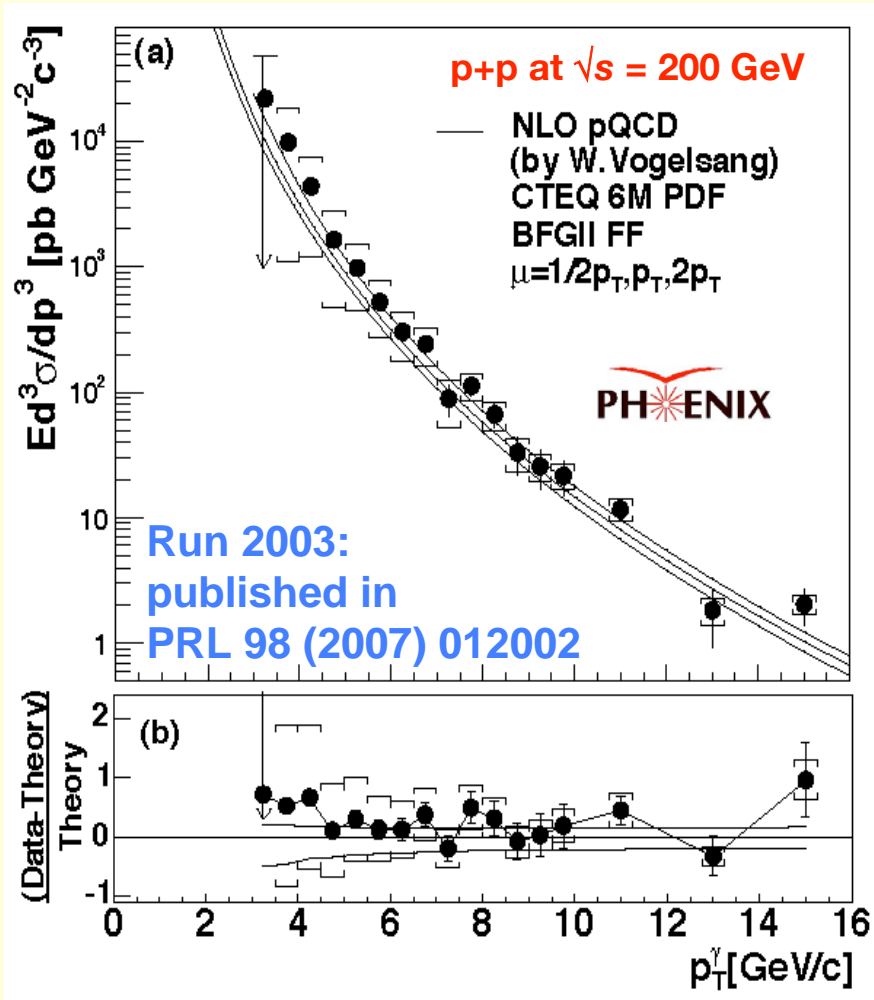
Agreement with NLO pQCD at √s = 200 GeV